Carrier Frequency Offset Estimation in MIMO-OFDM Systems

Thesis submitted in partial fulfillment

of the Requirements for the degree of

Master of Technology

in

Communication and Signal Processing

by

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Rourkela, Odisha, 769 008, India

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Under the guidance of

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2013

Dedicated to My Parents

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Certificate

This is to certify that the work in the thesis entitled **Carrier Frequency Estimation in MIMO-OFDM systems** by **Praween Kumar Nishad** is a record of an original research work carried out by him during 2012 - 2013 under my supervision and guidance in partial fulfillment of the requirements for the award of the degree of Master of Technology with the specialization of Communication and Signal Processing in the department of Electronics and Communication Engineering, National Institute of Technology Rourkela. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

Place: NIT Rourkela
Date: 21 May 2013

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Praween Kumar Nishad

Contents

Abstract

Orthogonal frequency division multiplexing (OFDM) is a popular method for high data rate wireless transmission. The performance of OFDM system is very sensitive to carrier frequency Offset (CFO), which introduces inter-carrier interference (ICI). Multi-input multi-output system used for increasing diversity gain and capacity of the system. Alamouti space time block code is used for MIMO transmission scheme.

The basic method is used for Carrier Frequency Offset Estimation in OFDM system. In cyclic prefix (CP) based estimation, the CFO can be found from the phase angle of the product of the CP and corresponding rear part of the OFDM symbol. In CFO estimation using a training symbol, the CFO estimation range can be increased by reducing the distance between two blocks of samples for correlation. This was made possible by using training symbol that is repetitive with shorter period. An analytic expression in the form of mean square error (MSE) of frequency offset synchronization is reported, and simulation results verify theoretical analysis.

Block-by-block CFO estimation is used in MIMO-OFDM system. In this algorithm we use block delay with other block and compare with the delay block. Analysis of the optimal size of block and minimization of the MSE of frequency estimator. We use S observation symbols they are grouped into two consecutive blocks with length A and S-A. The observation symbol, in each block is added sequentially and summed results are correlated block-wise.

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List of Abbreviations

OFDM	Orthogonal Frequency-Division Multiplexing.
ISI	Inter Symbol Interference.
FFT	Fast Fourier Transform.
IFFT	Inverse Fast Fourier Transform.
CFO	Carrier Frequency Offset.
STO	Symbol Time offset.
ICI	Inter-carrier Inter-ference.
MIMO	Multi-input Multi-output.
SISO	Singal-input Singal-output.
MSE	Mean Square Error.
CP	Cyclic Prefix.
SNR	Signal to Noise Ratio.
STBC	Space Time Block Code.
PAPR	Peak to Avarage Power Ratio.
MAI	Multi Antenna Interference.

1 Introduction

1.1 Digital Communication System

Basic digital communication system shown in Figure 1.1. A/D converter used to convert analog signal to digital signal i.e. binary signal (1/0). The source encoder compresses digital data and transmit. There are some basic source coding techniques are available like Shannon-Fano coding and Hoffman coding. Source coding provide less loss at the receiver side. The objective of source encoding is to remove redundancy from the source signal.

The information sequences pass though channel encoder which uses some redundancy in binary information than can be used at the receiver to overcome the noise effect in system and reliable communication. The output of channel encoder is passing through the modulator.

The digital modulator maps binary information sequence into some standard waveform i.e. electrical form, so that it can be transmitted into the channel. For example if 1 by cos (x) and 0 by sin (x) which is similar to BPSK modulation. The modulated waveform is being transmitted from the transmitter to the receiver through the channel. The signals are distorted in the channel because of channel noise like thermal noise, atmospheric noise, man-made noise etc. these noises are random in nature and unpredictable [2]. At the receiving side the digital demodulator consists of matched filter type detector or correlator detector that converts the received signal waveform into binary sequence, which represent the estimated word. The output from the demodulator is passed to the channel decoder, that recovers the information sequence from the knowledge of the transmitted code. After the decoder signal pass though the encoder which gives original information.

1.2 Introduction to OFDM

The total signal bandwidth, in a classical parallel data system, the signal bandwidth can be divided into N non-overlapping Frequency sub-channels i.e.frequency selective channel is converted into a group of narrow band flat-fading channel one channel across each carriers. Each sub-channel is modulated with a separate sym-

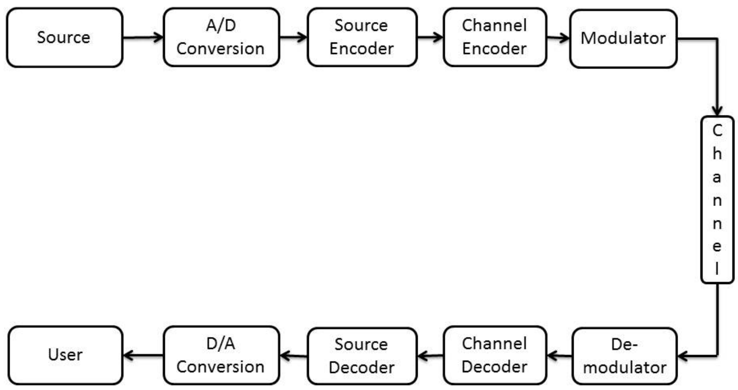

Figure 1.1: Block diagram of basic Digital Communication system.

bol (BPSK , QAM , etc..) and then the N sub-channels are frequency multiplexed. The general practice of avoiding spectral overlaps of sub-channels was applied to eliminate inter-carrier interference (ICI). This is shown in Figure 1.2. This resulted to insufficient utilization of the existing spectrum. An idea was proposed in the mid-1960s to deal with this useful through the development of frequency division multiplexing (FDM) but overlapping sub-channels. The sub-channels were arranged so that the side-bands of the individual carriers overlap without causing ICI. This principle is displayed in Figure 1.2. To achieve this the carriers must be mathematically orthogonal. From this constraint the idea of Orthogonal Frequency Division Multiplexing (OFDM) was born. The OFDM symbol corresponds to a composite signal of N symbols in a parallel form, which now has a duration of T_{sym}. Meanwhile, Figure 1.2 illustrates a typical realization of orthogonality among all sub-carriers. Furthermore it has been shown that this multi-carrier modulation can be implemented by IFFT and FFT in the transmitter and receiver, respectively [3].

OFDM took time to evolve to where it is today, utilized by various standards, such as 802.11 a/g and 802.16

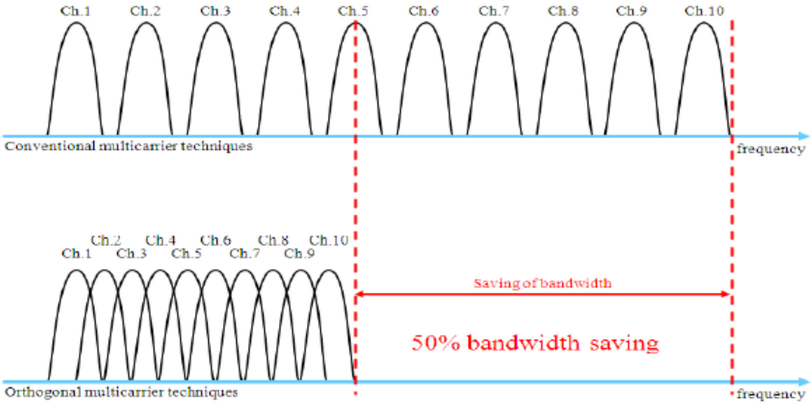

Figure 1.2: FDM and OFDM spectrum [4].

1.2.1 Orthogonality

Consider the time-limited complex exponential signals $\{e^{j2\pi f_k t}\}_{k=0}^{N-1}$ which represent the different sub-carriers at $f_k = \frac{k}{T_{sym}}$ in the OFDM signal, where$0 \leq t \leq T_{sym}$. These signals are defined to be orthogonal if the integral of the products for their common (fundamental) period is zero, that is [1],

$$\frac{1}{T_{sym}} \int_0^{T_{sym}} e^{j2\pi f_k t} e^{-j2\pi f_i t}\, dt. = \frac{1}{T_{sym}} \int_0^{T_{sym}} e^{j2\pi \frac{k}{T_{sym}} t} e^{-j2\pi \frac{i}{T_{sym}} t}\, dt. \tag{1.1}$$

$$\text{Orthogonality} = \begin{cases} 1 & \text{if k = i} \\ 0 & \text{otherwise} \end{cases}$$

Taking the discrete samples with the sampling instances at t = nT_s = nT_{sym}= N, n = 0, 1, 2, ...; N-1, can be written in the discrete time domain as [1],

$$\frac{1}{N} \sum_{n=0} N-1 e^{j2\pi \frac{k}{T_{sym}} nT_s} e^{-j2\pi \frac{i}{T} nT_s} = \frac{1}{N} \sum_{n=0} N-1 e^{j2\pi \frac{k}{T_{sym}} \frac{nT}{N}} e^{-j2\pi \frac{i}{T} \frac{nT_{sym}}{N}} \tag{1.2}$$

$$\text{Orthogonality} = \begin{cases} 1 & \text{if k = i} \\ 0 & \text{otherwise} \end{cases}$$

The above orthogonality is an essential condition for the OFDM signal to be ICI-free.

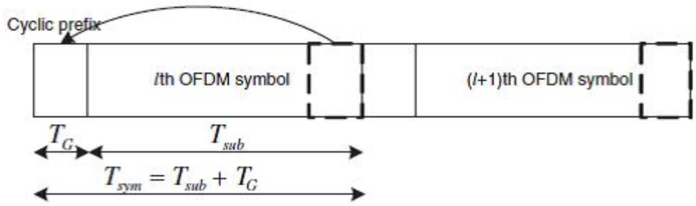

Figure 1.3: OFDM symbols with CP [1].

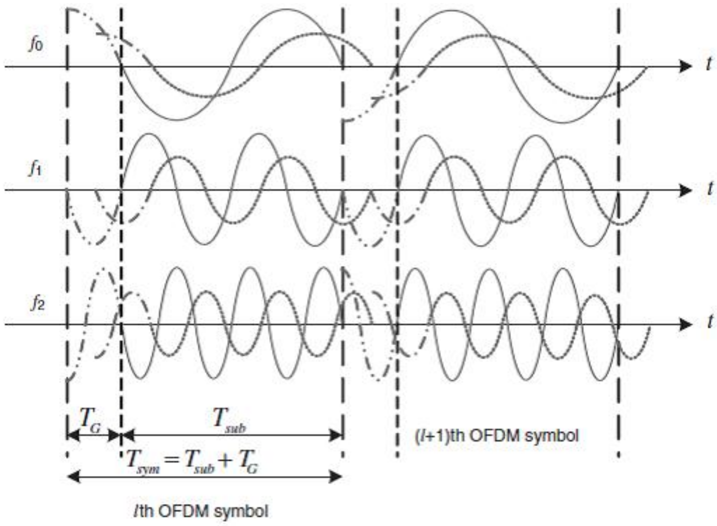

Figure 1.4: ISI effect of a multipath channel for each sub-carrier [1].

1.2.2 Cyclic Prefix (CP)

The OFDM guard interval can be inserted in two different ways. One is the zero padding (ZP) that pads the guard interval with zeros. The other is the cyclic extension of the OFDM symbol (for some continuity) with CP (cyclic prefix) or CS (cyclic suffix). CP is to extend the OFDM symbol by copying the last samples of the OFDM symbol into its front. Figure 1.3 shows OFDM symbols with CP and Figure 1.4 shows ISI effect of a multipath channel for each sub carrier. Cyclic prefix should be greater than delay spread of channel to avoid inter OFDM symbol interference. CP is simply repeating symbols dost not constitute any information, hence the effect of addition of long CP is loss in throughput of system.

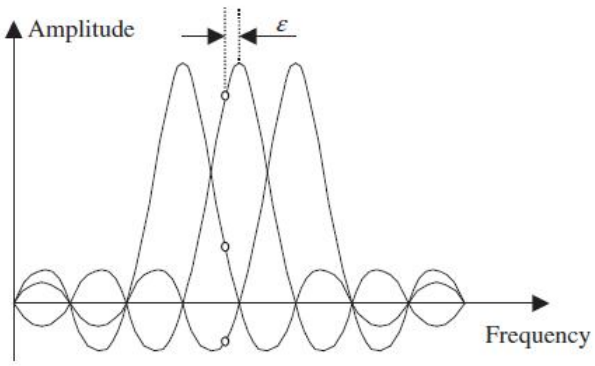

Figure 1.5: Inter-carrier interference (ICI) subject to CFO [1].

1.2.3 Effect of CFO and STO

The baseband transmit signal is converted up to the passband by a carrier modulation and then, converted down to the baseband by using a local carrier signal of (hopefully) the same carrier frequency at the receiver. In general, there are two types of distortion associated with the carrier signal. One is the phase noise due to the instability of carrier signal generators used at the transmitter and receiver, which can be modeled as a zero-mean Wiener random process. The other is the carrier frequency offset (CFO) caused by Doppler frequency. CFO destroys the orthogonality between the sub-carriers which is shown in Figure 1.5. Table 1.1 shows the effect of the CFO in receiving signal in frequency domain with shifting of ξ and time domain multiplying with the exponential term and Table 1.5 shows the Doppler frequency and normalized CFO for some standard systems like DMB, 3GPP and mobile WiMAX [5], [6].

Table 1.1: The effect of CFO on the received signal

	Received signal	Effect of CFO ξ on the received signal
Time-domain signal	y[n]	$e^{\frac{j2\pi n\xi}{N}} x[n]$
Frequency-domain signal	Y[K]	X[k - ξ]

IFFT and FFT are the fundamental functions required for the modulation and demodulation at the transmitter and receiver of OFDM systems, respectively. In order to take the N-Point FFT in the receiver, we need the exact samples

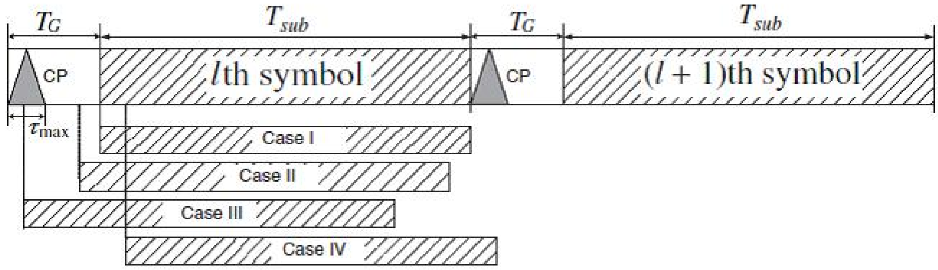

Figure 1.6: Four different cases of OFDM symbol starting point subject to STO.

of the transmitted signal for the OFDM symbol duration. In other words, a symbol-timing synchronization must be performed to detect the starting point of each OFDM symbol (with the CP removed), which facilitates obtaining the exact samples. Table 1.2 shows how the STO of δ samples affects the received symbols in the time and frequency domain where the effects of channel and noise are neglected for simplicity of exposition. Four different cases of OFDM symbol starting point subject to STO. All these foure cases shown in Figure 1.6.

- Case I: This is the case when the estimated starting point of OFDM symbol coincides with the exact timing, preserving the orthogonality among subcarrier frequency components. In this case, the OFDM symbol can be perfectly recovered without any type of interference.

- Case II: This is the case when the estimated starting point of OFDM symbol is before the exact point, yet after the end of the (lagged) channel response to the previous OFDM symbol. In this case, the lth symbol is not overlapped with the previous$(l-1)^{th}$ OFDM symbol, that is, without incurring any ISI by the previous symbol in this case.

- Case III: This is the case when the starting point of the OFDM symbol is estimated to exist prior to the end of the (lagged) channel response to the previous OFDM symbol, and thus, the symbol timing is too early to avoid the ISI. In this case, the orthogonality among subcarrier components is destroyed by the ISI (from the previous symbol) and furthermore, ICI (Inter- Channel Interference) occurs.

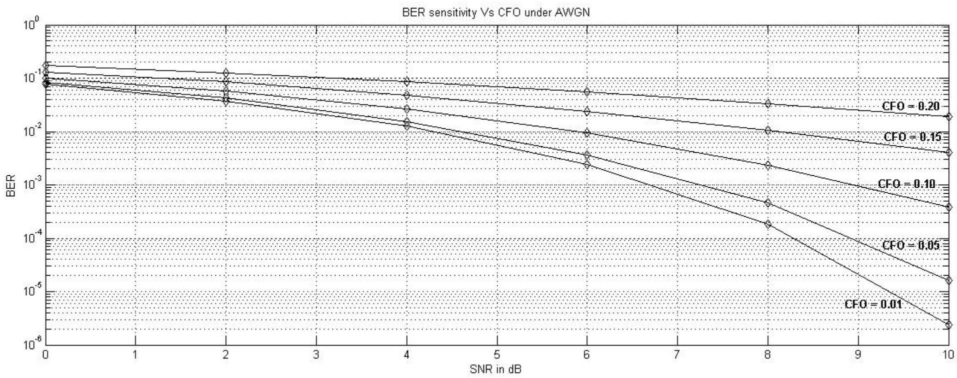

Figure 1.7: BER sensitivity Vs CFO under AWGN channel noise.

- Case IV: This is the case when the estimated starting point of the OFDM symbol is after the exact point, which means the symbol timing is a little later than the exact one [7].

Table 1.2: The effect of symbol time offset (STO)

	Received signal	Effect of STO δ on the received signal
Time-domain signal	y[n]	X[k - δ]
Frequency-domain signal	Y[K]	$e^{\frac{j2\pi n\delta}{N}} x[n]$

Table 1.3: Doppler frequency and normalized CFO: an example.

Systems	Carrier Frequencyf_c	Sub-carrier spacing(Δf)	Velocity	Maximum Doppler frequency(f_d)	Normalized CFO(ξ)
DMB	375MHz	1KHz	120Km/h	41.67Hz	0.042
3GPP	2GHz	15KHz	120Km/h	222.22Hz	0.0148
Mobile WiMAX	2.3GHz	9.765KHz	120Km/h	255.55Hz	0.0263

1.2.4 Advantages of OFDM Systems

- Efficient implementation using Fast Fourier Transform (FFT).
- High spectral efficiency as compared to other double sideband modulation schemes, spread spectrum.
- Robust against inter-symbol interference (ISI) and fading caused by multipath propagation.

- Can easily adapt to severe channel conditions without complex time-domain equalization.
- Robust against narrow-band co-channel interference.
- Low sensitivity to time synchronization errors.

1.2.5 Disadvantages of OFDM Systems

- Sensitive to Doppler shift.
- Sensitive to frequency synchronization problems.
- High peak-to-average-power ratio (PAPR), requiring linear transmitter circuitry, which suffers from poor power efficiency.
- Loss of efficiency caused by cyclic prefix/guard interval.

[8] [4] [9] [10] [11] [12] [13] [14]

1.3 Literature Survey

A number of approaches have dealt with CFO estimation in a OFDM (SIS0) systems [10], [15], [16], [17], [18], [19]. According to whether the CFO estimators use training sequences or not, they can be classified as-

1.3.1 Time-Domain Estimation Techniques for CFO

For CFO estimation in the time domain, cyclic prefix (CP) or training symbol is used.

- cyclic prefix (CP) based Estimation.
- Blind CFO Estimation [15], [16].
- Training-based CFO Estimation [10], [17], [18], [19].

1.3.2 Frequency-Domain Estimation Techniques for CFO

If two identical training symbols are transmitted consecutively, the corresponding signals with CFO of ξ are related with each other. which is a well-known approach by Moose [10].

Similar to SISO-OFDM, MIMO-OFDM is also very sensitive to CFO. Moreover, for MIMO-OFDM, there exists multi-antenna interference (MAI) in the received antennas between the received signals from different transmit antennas. The MAI makes CFO estimation more difficult as compare to SISO-OFDM systems, and a optimum size training sequence design is required for training-based CFO estimation in high range of CFOs. However, unlike SISO- OFDM, only a few CFO estimation in MIMO-OFDM system works have appeared in the literature. In [7], a blind kurtosis-based CFO estimator for MIMO-OFDM was developed. In that estimation they introduced a random-hopping scheme which robustifies the CFO estimator against channel nulls. For training-based CFO estimators, the overviews concerning the necessary changes to the training sequences and the corresponding CFO estimators when extending SISO-OFDM to MIMO-OFDM were provided in [20], [21]. However, with the provided training sequences in [20], satisfactory CFO estimation performance cannot be achieved. With the training sequences in [21], the training period grows linearly with the number of transmit antennas, which results in an increased overhead. In [22], a white sequence based maximum likelihood (ML) CFO estimator was addressed for MIMO, while a hopping pilot based CFO estimator was proposed for MIMO-OFDM in [23]. [22], [23] require a large point discrete Fourier transform (DFT) operation for CFO Estimation. In [13] CFO estimator only applied to flat-fading MIMO channels.

1.4 Motivation

OFDM system carries the message data on orthogonal sub-carriers for parallel transmission, combating the distortion caused by the frequency-selective channel or equivalently, the inter-symbol-interference in the multi-path fading channel. However, the advantage of the OFDM can be useful only when the orthogonality is maintained. In case the orthogonality is not sufficiently warranted by any means, its performance may be degraded due to inter-symbol interference (ISI) and inter-channel interference (ICI) [1].

- The carrier frequency offset (CFO) caused by Doppler frequency shift f_d and physically inherent nature of the oscillators.
- Presence of a carrier frequency offset can introduce several distortion in a OFDM system as it results in loss of orthogonality among-st the sub-carrier.
- Consider frequency offset Δf such that carrier frequency offset.
  - $\frac{\Delta f}{\frac{B}{N}} = \xi$
  - ξ=normalized frequency offset.
- Normalized frequency offset ξ.

1.5 Objective of the work

The main objective of this work is to present a carrier frequency offset estimation in OFDM systems and MIMO-OFDM systems. Various analysis and investigations are needed in support of the above statement which includes:

- Generation of training sequence with the optimal length.
- Selection of optimal block size.
- Improving MSE performance by increasing the CFO ranges.
- Optimal length of repetitive pattern, and number of pilot tones for minimization of MSE.

1.6 Thesis Organization

This thesis is organized into four chapters. The current chapter begins with the background details of the OFDM systems.The objective for this thesis work is framed after literature review and this chapter ends with the outline of the thesis.

- Chapter- 2 CFO Estimation in OFDM Systems.

  This chapter discusses in more detail about SISO-OFDM systems and estimation of carrier frequency offset (CFO) using four different estimation methods.

- Chapter-3 CFO Estimation in MIMO-OFDM Systems.

  MIMO-OFDM systems and carrier frequency offset estimation is discussed in this chapter. space time block coding for increasing the diversity of systems. and finally CFO estimation in MIMO-OFDM systems.

- Chapter- 4 Concluding remarks.

  The last chapter is a summary and discussion on the work presented in this thesis where also further work is outlined.

2

CFO Estimation in OFDM Systems

2.1 Introduction

OFDM system is widely used in multi-carrier modulation schemes. In this modulation all sub-carriers are orthogonal to each other, which increases the bandwidth efficiency of the system. OFDM transmission frequency channel converts in the group of narrow band flat fading channel, one channel across each sub-channel. OFDM modulation and de-modulation is implemented efficiently by inverse discrete Fourier transform and discrete Fourier transform at the transmitter and receiver respectively [5]. Cyclic prefix (CP) is used for extension of OFDM symbol in time domain which increases the robustness of OFDM system against inter symbol interference (ISI). OFDM has been used in great extent application like wireless local area network IEEE802.11a/g standard, wireless metropolitan network, digital audio broadcasting and terrestrial video broadcasting standard.

OFDM is very sensitive to time and frequency synchronization. The synchronization problem consists of two major parts: carrier frequency offset (CFO) and symbol time offset (STO). This is due to Doppler shift and a mismatch between the local oscillator at the transmitter and receiver. In STO, time domain δ sample and phase shift offset is affected in the frequency domain. Frequency synchronization error destroys the orthogonality among the sub carriers which causes inter carrier interference (ICI) [9]. Therefore the CFO synchronization is essential to OFDM system. The CFO estimation has been extensively investigated for single input single output (SISO) and for multiple input multiple output (MIMO) OFDM based system. The normalized CFO can be divided into two parts which are integral CFO (IFO) ξ_i and fractional CFO (FFO) ξ_f. IFO produce a cyclic shift by ξ_i in receiver side to corresponding sub carrier it does not destroy orthogonality among the sub carrier frequency component and FFO destroys the orthogonality between the sub carriers.

For CFO estimation in time domain, cyclic prefix (CP) and training sequence are used. CP based estimation has analyzed assuming negligible channel effect. CFO can be found from the phase angle of the product of CP and the corresponding part of an OFDM symbol, the average has taken over the CP intervals and in training sequence estimation using training symbol that is repetitive with some shorter period.

In CFO estimation using frequency domain, this technique involves the comparison of the phase of the each sub carrier to successive symbol, the phase shift in symbol due to the carrier frequency offset. Two different estimation modes for CFO estimation in pilot based estimation method is used which are acquisition and tracking mode. In the acquisition mode large range of CFO estimation is done and in tracking mode only the fine CFO is estimated. Initially we assume that acquisition estimation is already performed and hence fine CFO estimation is performed in this paper. All simulation results show mean square error (MSE) with respect to different signal to noise ratio (SNR) in db and comparied for training sequence with ratio of OFDM symbol to repetitive sequence length with respect to different CFO value.

2.2 System Model

In OFDM transmission scheme a wide-band channel divided into N orthogonal narrow-band sub-channels. N Point IFFT and FFT are used to implement OFDM Modulation and Demodulation. The transmitter maps the message bits X_m into a sequence of BPSK or QAM symbols which are subsequently converted into an N parallel bit stream. Each of N symbols from the serial-to-parallel (S/P) conversion is modulated on the different sub-carriers.

Let $X_l[k]$ denote the l^{th} transmit symbol at k^{th} sub-carrier l = 0, 2, ... ∞ . k = 0, 1, 2, ... N-1, T_{sym} = NT_s OFDM symbol length [1].

OFDM signal at the k^{th} sub-carrier,

$$\psi_{lk}(t) = \begin{cases} e^{2\pi j f_k(t-lTsym)} & 0 < t \leq T_{sym} \\ 0 & \text{eleswhere} \end{cases} \tag{2.1}$$

The passband and baseband OFDM in the continuous time domain.

$$x_l(t) = Re\left\{\frac{1}{T_{sym}}\sum_{l=0}^{\infty}\left\{\sum_{k=0}^{\infty} x_l[k]\psi_{lk}(t)\right\}\right\} \tag{2.2}$$

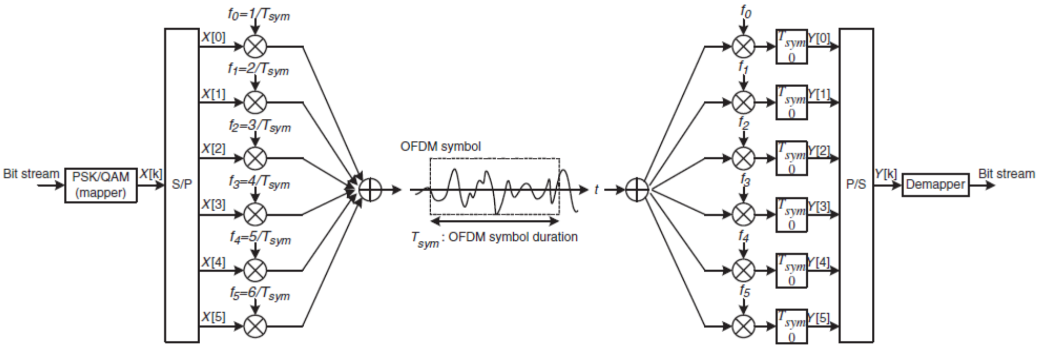

Figure 2.1: OFDM Modulation and Demodulation [1].

The continuous time baseband OFDM signal is sampled at t = lT_{sym}+nT_s with T_s = T_{sym}/N and f_k = k/T_{sym} to corresponding discrete time OFDM signal.

$$x_l[n] = \sum_{k=0}^{N-1} X_l[k]e^{2\pi jkn/N} \tag{2.3}$$

for n = 0, 1, ... N-1 the received baseband symbol with considering the effect of channel and noise at the receiver $\{y_l[n]\}_{n=0}^{N-1}$ the sample value of the received ODFM symbol $y_l(t)$ at t = lT_{sym}+nT_s is

$$y_l[k] = \sum_{n=0}^{N-1} H_l[n]y_l[n]e^{-2\pi jkn/N} + W_l[n] \tag{2.4}$$

The received baseband symbols under the presence of CFO ξ and STO δ

$$y_l[n] = \frac{1}{N}\sum_{k=0}^{N-1} H_l[k]X_l[k]e^{2\pi j(k+\xi)(n+\delta)/N} + W_l[k] \tag{2.5}$$

Where ξ is the normalized frequency offset (the ratio of actual frequency offset to the inter carrier spacing Δf) and $w_l[n]$ is the complex envelope of additive white Gaussian noise (AWGN).

the k^{th} element of DFT sequence consist of three component [10].

$$y_k = (X_kH_k)\left\{\frac{sin\pi\xi}{Nsin(\pi\xi/N)}\right\}e^{\pi j(N-1)/N} + I_k + W_k \tag{2.6}$$

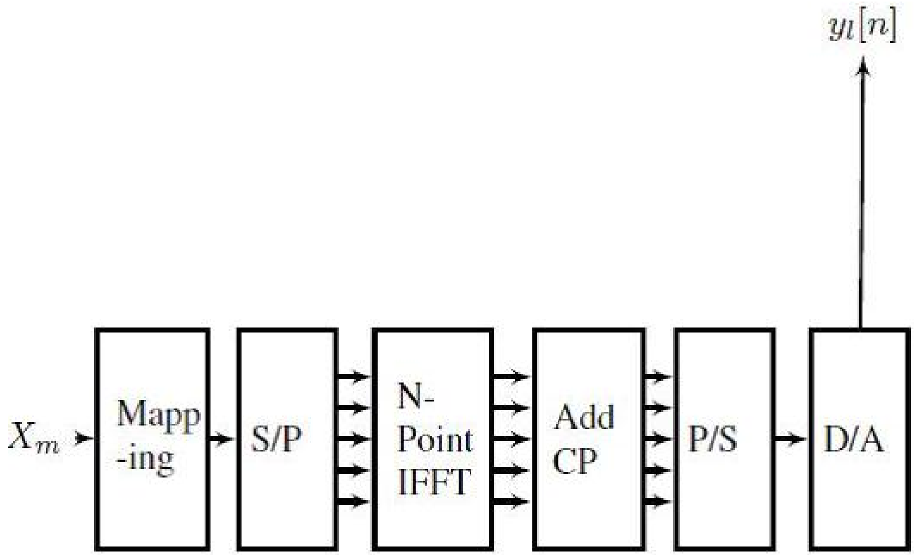

Figure 2.2: OFDM Transmitter block.

Here the first component is modulation and second component is ICI caused by the frequency offset.

$$I_k = \sum_{l=0,l\neq k}^{N-1} (X_l H_l) \left\{ \frac{sin\pi\xi}{Nsin(\pi\xi(l-k+\xi)/N)} \right\} .e^{j\phi} \tag{2.7}$$

$$e^{j\phi} = e^{\pi j\xi(N-1)/Ne^{-\pi j(l-k)/N}} \tag{2.8}$$

In order to evaluate the statistical properties for estimation of the ICI, some further assumptions are necessary. Specifically, it will be assumed that E $[I_k] = 0$ and E $[X_k X_l^*] = |x|^2 \delta_{lk}$ the modulation values have zero mean and are uncorrelated. With this provision E$[I_k] = 0$.

2.3 Proposed Method

2.3.1 CP Based:

With perfect symbol synchronization, a CFO of ξ results in a phase rotation of $2\pi n\xi/N$ in the received signal. Under the assumption of negligible channel effect, the phase difference between CP and the corresponding rear part of an OFDM symbol (spaced N samples apart) is 2πNξ/N $= 2\pi\xi$. Then, the CFO can be found from the phase angle of the product of CP and the corresponding rear part of an OFDM symbol,

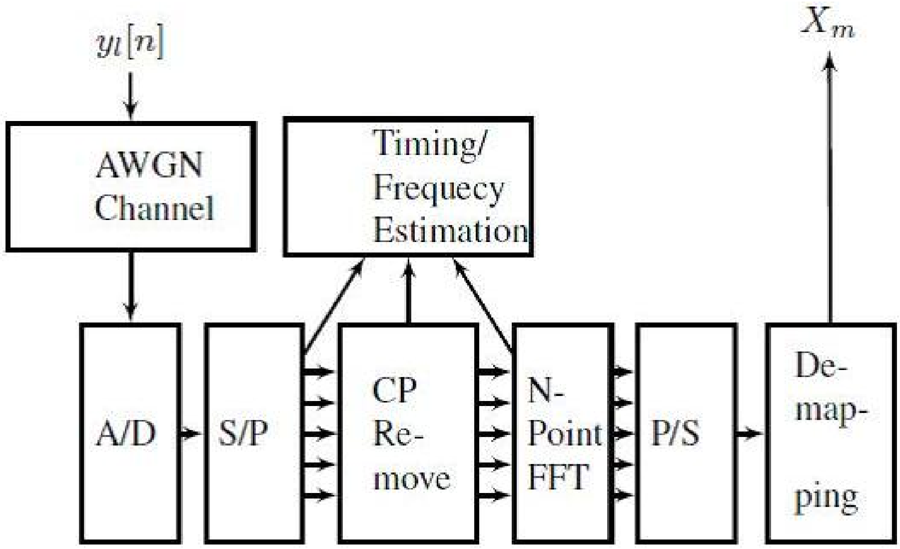

Figure 2.3: OFDM Receiver block.

CFO estimation using CP based.

$$\widetilde{\xi} = (1/2\pi)arg\left\{y_l^*[n]y_l[n+N]\right\} \tag{2.9}$$

n = -1, -2, ... $-N_g$. In order to reduce the noise effect, its average can be taken over the samples in a CP interval.

$$\widetilde{\xi} = (1/2\pi)arg\left\{\sum_{n=-N_g}^{-1} y_l^*[n]y_l[n+N]\right\} \tag{2.10}$$

Arg() performed $tan^{-1}()$, the range of the CFO estimation is [-0.5+0.5] and mean square error performed by $\widetilde{\xi} - \xi$.

2.3.2 Symbol Based:

Two identical training symbols are transmitted consecutively and the corresponding signals with CFO of ξ are related with each other. For an OFDM transmission symbol at one receiver with an assumption of the absence of noise the 2N Point sequence is [10]

$$r_n = \frac{1}{N}\sum_{k=0}^{N-1} H_k X_k e^{2\pi j(k+\xi)/N} \tag{2.11}$$

n = 0, 1, ... 2N-1,

The k^{th} element of the N Point DFT of the first N Points (2.11) is

$$R_{1k} = \sum_{n=0}^{N-1} r_n e^{-2\pi jkn/N} \tag{2.12}$$

k = 0, 1, 2, ... N-1,

The second half of the sequence is-

$$R_{2k} = \sum_{n=0}^{N-1} r_n + N e^{-2\pi jkn/N} \tag{2.13}$$

$r_n + N = r_n e^{2\pi j\xi}$, $R_{2k} = R_{1k} e^{2\pi j\xi}$, including the AWGN noise $Y_{1k} = R_{1k} + W_{1k}$
$Y_{2k} = R_{1k} e^{2\pi j\xi} + W_{2k}$; k = 0, 1, 2, ... N-1.

Observe that between the first and second DFT symbols, both ICI and signal are altered in exactly the same way, by a phase shift proportional to frequency offset. Therefore, if frequency offset ξ is estimated using above observations, it is possible to obtain accurate estimation even when the offset is too large for satisfactory data demodulation [10].

$$\widetilde{\xi} = (\frac{1}{2\pi}) tan^{-1} \left\{ \frac{\sum_{k=0}^{N-1} Im[Y_{2k} Y_{1k}^*]}{\sum_{k=0}^{N-1} Re[Y_{2k} Y_{1k}^*]} \right\} \tag{2.14}$$

The limit for accurate estimation by Equation (2.14) is $|\xi| \leq 0.5$.

2.3.3 Training Sequence Based:

CFO only within the range$|\xi| \leq 0.5$, Since CFO can be large at initial synchronization stage, we may need estimation techniques that can cover wider CFO range. The range of CFO estimation can be increased by reducing the distance between two blocks of samples for correlation. This is made possible by using training symbols that are repetitive with some shorter period. Let D represents the ratio of the OFDM symbol length to the length of a repetitive pattern. Let the transmitter sends the training symbols with D repetitive patterns in the time domain, which generated combo-type signal in the frequency domain after taking IFFT.

$$X_l[k] = \begin{cases} A_m & \text{if}, k = D.i, i = 0, 1, ...(N/D - 1) \\ 0 & \text{eleswhere} \end{cases} \tag{2.15}$$

where A_m represents an M-ary symbol and N/D is an integer and $x_l[n]$ and $X_l[n + N/D]$ are identical. After receiving repetitive length data sequence, receiver can make CFO estimation as [12].

$$\widetilde{\xi} = (D/2\pi)arg \left\{ \sum_{n=0}^{N/D} y_l^*[n] y_l[n + N/D] \right\} \tag{2.16}$$

The estimation range in this technique is $|\xi| \leq D/2$, which becomes wider as D increases and number of samples for the computation of correlation is reduced by 1/D, which degrade the MSE performance of OFDM system. In other words, the increase in estimation range is obtained at the sacrifice of MSE (mean square error) performance. Figure 2.7 shows the estimation range of MSE vs. CFO performance for D = 2 and 4. simulation generates the plot which shows that the range of CFO is increased when the value of D is increasing.

$$\widetilde{\xi} = (D/2\pi)arg \left\{ \sum_{m=0}^{D-2} \sum_{n=0}^{N/D-1} y_l^*[n + mN/D] y_l[n + (m+1)N/D] \right\} \tag{2.17}$$

The MSE performance can be improved without reducing the estimation range of CFO by taking the average of the estimates with the repetitive patterns of the shorter period.

2.3.4 Pilot Based:

Pilot tones inserted in the frequency domain and transmit every OFDM symbol for CFO tracking. The signals are transformed into $Y_l[k]_{k=0}^{N-1}$ and $Y_{l+D}[k]_{k=0}^{N-1}$ though FFT, from which pilot tones are extracted. After estimating CFO from pilot tones in the frequency domain, the signal is compensated with the estimated CFO in the time domain. In this process, two different estimation modes for CFO estimation are Implemented: acquisition and tracking modes. In the acquisition mode, a large range of CFO including an integer CFO is estimated and in the tracking mode, only fine CFO is estimated. The integer CFO is estimated by [11].

$$\widetilde{\xi} = (\frac{1}{2\pi T_{sub}})max(\xi)\left\{|\sum_{j=0}^{L-1} Y_{l+D}[p[j],\xi]Y_l^*[p[j],\xi]X_{l+D}^*[p[j]]X_l[p[j]]|\right\} \quad (2.18)$$

where L, p[j], and $X_l[p[j]]$ denote the number of pilot tones, location of the j^{th} pilot tone, and the pilot tone located at p[j] in the frequency domain at the l^{th} symbol period [1].

2.4 Results & Comparison

CFO estimation is done by using four different techniques, first one by using Equation (2.10), the phase difference between CP and the corresponding rear part of an OFDM symbol. Second by using Equation (2.14), the phase difference between two repetitive preambles. Third by using Equation (2.16), training sequence with D integer i.e. ratio of the OFDM symbol length to the length of a repetitive pattern, taking D = 1, 2 and 4, in this estimation range of CFO increases but MSE performance decreases with increasing the value of D. Simulation Figure 2.6 shown for D = 1, 2 and 4, for MSE vs CFO performance shows in Figure 2.7, in this figure D = 2 and D = 4, the range of CFO is increasing for D = 4 comparisons with D = 2, taking signal to noise ratio 6 dB. Fourth one by using Equation (2.18) estimation between pilot tones in two consecutive OFDM symbols. Figure 2.4 and Figure 2.5 show MSE performance for three different techniques with taking CFO = 0.15 and 0.30. Pilot tone based estimation is better then CP and Preamble based estimation. Performances of estimation techniques vary depending on the number of samples in CP, the number of samples in preamble, and the number of pilot tones, used for CFO estimation. Simulations are performed to verify the accuracy of MSE analysis.

The OFDM system parameters are CFO = 0.15 and CFO = 0.30, N = 128, $N_g = 16$,$N_{ps} = 4$ (Pilot spacing), Number of pilots $N_p = 32$, signal to noise ratio (SNR) 0 to 30 db, D = 1, 2 and 4. For OFDM mapping QAM modulation used and taking signal energy $E_s = 1$.

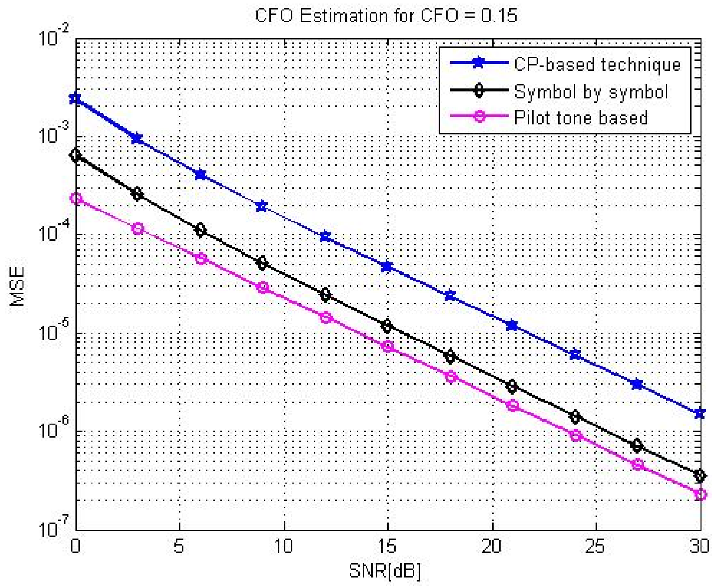

Figure 2.4: Simulation With CFO = 0.15.

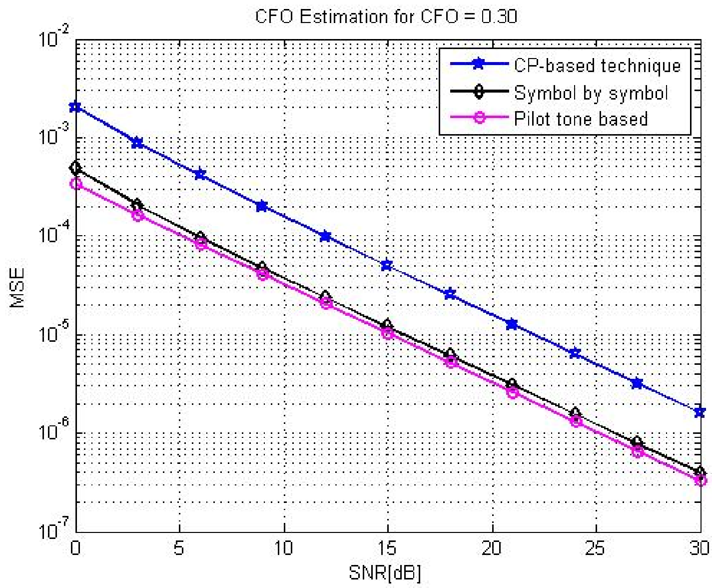

Figure 2.5: Simulation With CFO = 0.30.

2.5 Conclusion

In this section frequency synchronization in an OFDM system is studied. The simulation results show the superior performance of our proposed scheme in AWGN channel. Pilot based mean square estimation (MSE) performance is superior then compare to CP based and symbol based.By using repeated sequences with different value of D, CFO has been estimated.

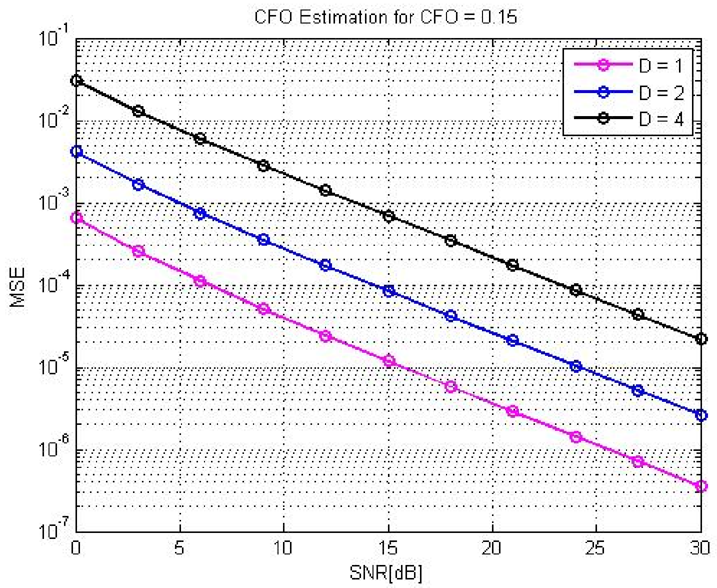

Figure 2.6: Training Sequence Based.

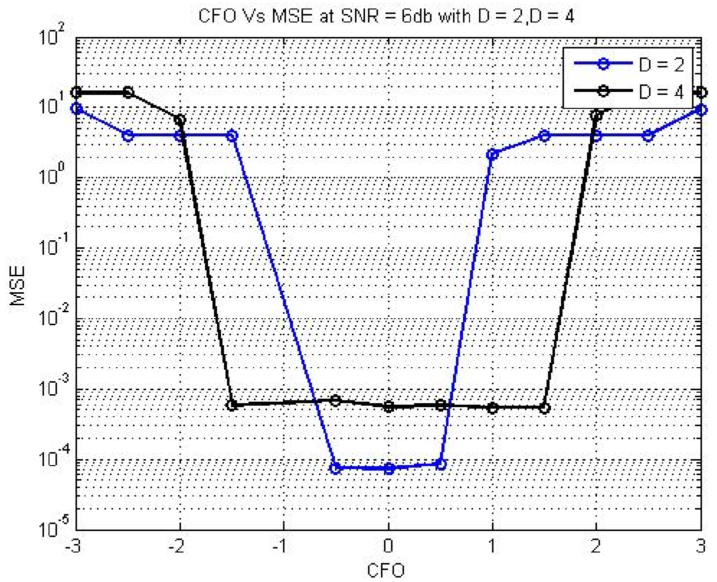

Figure 2.7: MSE vs CFO.

Further intensive research is needed in MIMO-OFDM system considering the generalized system model. Where the CFO and propagation delay between each transmit antenna and receive antenna are possibly different.

3 CFO Estimation in MIMO-OFDM Systems

3.1 Introduction

The key challenge faced by future wireless communication systems is to provide high-data-rate wireless access at high quality of service (QoS). Combined with the facts that spectrum is a scarce resource and propagation conditions are hostile due to fading (caused by destructive addition of multipath components) and interference from other users, this requirement calls for means to radically increase spectral efficiency and to improve link reliability. Multiple-input multiple-output (MIMO) wireless technology [1] seems to meet these demands by offering increased spectral efficiency through spatial multiplexing gain, and improved link reliability due to antenna diversity gain. Even though there is still a large number of open research problems in the area of MIMO wireless, both from a theoretical perspective and a hardware implementation perspective, the technology has reached a stage where it can be considered ready for use in practical systems. In fact, the first products based on MIMO technology have become available, for example, the pre-IEEE 802.11n wireless local area network (WLAN) systems by Airgo Networks, Inc., Atheros Communications, Inc., Broadcom Corporation, Marvell Semiconductor, Inc., and Metalink Technologies, Inc. Current industry trends suggest that large-scale deployment of MIMO wireless systems will initially be seen in WLANs and in wireless metropolitan area networks (WMANs). Corresponding standards currently. The existing applications of WLANs consist of unlicensed operating at industrial, and medical (ISM) frequency around 2.45 and 5.8 GHz and licensed cellular system operating at 18.19 GHz which can support data rate up to 54Mb/s by using orthogonal frequency division multiplexing (OFDM) technique. Recently, there has been an IEEE 802.11n technical proposal supporting high data rate based on multiple input and multiple output (MIMO) with OFDM.

The goal of this chapter is to provide a high level review of the basics of MIMO-OFDM wireless systems with a focus on transceiver design, multiuser systems, and hardware implementation aspects.MIMO-OFDM is a combination of MIMO(multi iput multi output) communication with OFDM. MIMO-OFDM converts a frequency selective MIMO channel into multiple paraller flat fading MIMO channels.

In MIMO frequency selective channel ISI occurs between current and previous transmitted vector, so MIMO-OFDM system one need to perform the IDFT or IFFT opreration at each transmitted antenna. MMSE (minimum mean squared error) or ZF (zero forcing) receiver are uesd for the receiving MIMO-OFDM symbols.

OFDM system is quite sensitive to frequency synchronization error, which may lead to several degradation in system performance [4]. We consider, after coarse synchronization residual carrier frequency offset estimation in MIMO-OFDM system. A number of algorithm in literature [5 - 9] to estimate a phase error using pilots. In this chapter we suggest an improved residual CFO tracking algorithm via block-by-block in MIMO-OFDM system. In this algorithm we use block delay with other next block and compare with the delay block. To demonstrate the efficiency of proposed CFO estimator, we compare it with the other existing algorithm in terms of Mean Square error (MSE), estimation range, complexity, based on the simulation and theoretical analysis.

3.2 MIMO System

Doppler spread are the most important factors to consider in characterizing the SISO system. In the MIMO system which employs multiple antennas in the transmitter and/or receiver, the correlation between transmit and receive antenna is an important aspect of the MIMO channel. MIMO can increases the data rate by transmitting several information streams in parallel (same frequency at same time) same transmit power. It depends on the angle-of-arrival (AoA) of each multi-path component. Figure.3.1 shows $N_R \times N_T$ MIMO system model x_1 x_2 . . . . . . x_{N_T} are transmitted symbols corresponding y_1 y_2. . . . . . . y_{N_R} received antenna and h_{11} . . . . $h_{N_R N_T}$ are the channel impulse response of the systems. MIMO system model with the R^{th} received antenna and T^{th} transmit antenna, x transmit vector, y received vector, h_{ij} is channel coefficient between the i^{th} received antenna and

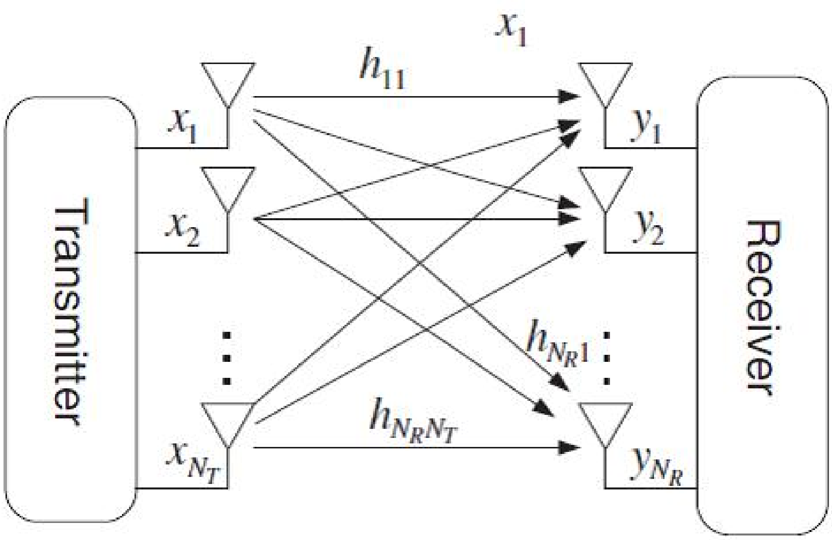

Figure 3.1: $N_R \times N_T$ MIMO system.

j^{th} transmit antenna. So MIMO channel matrix is

$$H_{r,t} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,t} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{r,1} & h_{r,2} & \cdots & h_{r,t} \end{bmatrix}$$

Hence MIMO system model can be write with $\widetilde{y}$ in r dimensional received vector, H in $r \times t$ channel matrix, $\widetilde{x}$ in t dimensional transmit vector and $\widetilde{n}$ in r dimension noise.

$$\widetilde{y} = H\widetilde{x} + \widetilde{n} \tag{3.1}$$

We can write MIMO system in matrix form as follows :

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_r \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,t} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{r,1} & h_{r,2} & \cdots & h_{r,t} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_t \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_r \end{bmatrix}$$

3.2.1 Spatial Multiplexing

Spatial multiplexing yields a linear (in the minimum of the number of transmit and receive antennas) capacity increase, compared to systems with a single antenna at one or both sides of the link, at no additional power or bandwidth expenditure [24] , [25]. The corresponding gain is available if the propagation channel exhibits rich scattering and can be realized by the simultaneous transmission of independent data streams in the same frequency band. The receiver exploits differences in the spatial signatures induced by the MIMO channel onto the multiplexed data streams to separate the different signals, thereby realizing a capacity gain.

3.2.2 Diversity

Diversity can be employed to improve performance of wireless system through controlling or combating fading. Diversity leads to improved link reliability by rendering the channel less fading and by increasing the robustness to co-channel interference. Diversity gain is obtained by transmitting the data signal over multiple (ideally) independently fading dimensions in time, frequency, and space and by performing proper combining in the receiver. Spatial (i.e., antenna) diversity is particularly attractive when compared to time or frequency diversity, as it does not incur an expenditure in transmission time or bandwidth, respectively. Space-time coding [26] realizes spatial diversity gain in systems with multiple transmit antennas without requiring channel knowledge at the transmitter. In one transmitter one receiver system if channel is in under deep fade in this condition we can not receive any signal. Avoid this problem increase number of links. Figure 3.2 shows transmitter link is under deep fading in this condition we can not receive desired signal at receiver. Avoid deep fade condition MIMO system is used which shows in Figure 3.3.

3.2.3 Array Gain

Array gain can be realized both at the transmitter and the receiver. It requires channel knowledge for coherent combining and results in an increase in average receive signal-to-noise ratio (SNR) and hence improved coverage.

Multiple antennas at one or both sides of the wireless link can be used to cancel or reduce co-channel interference, and hence improve cellular system capacity.

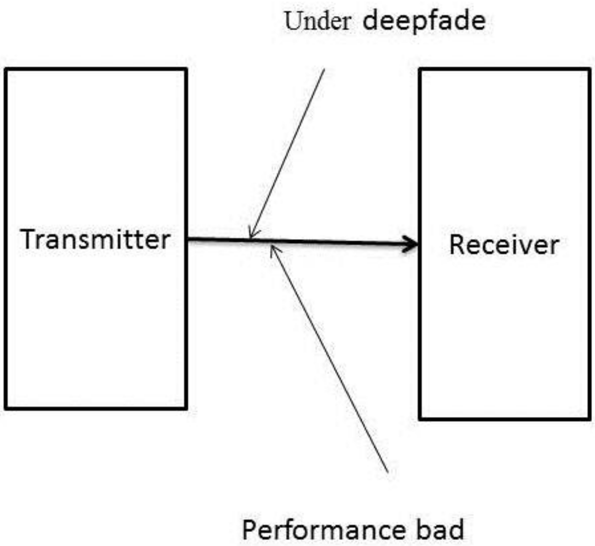

Figure 3.2: Link is in under Deep fading for one Transmitter and one Receiver.

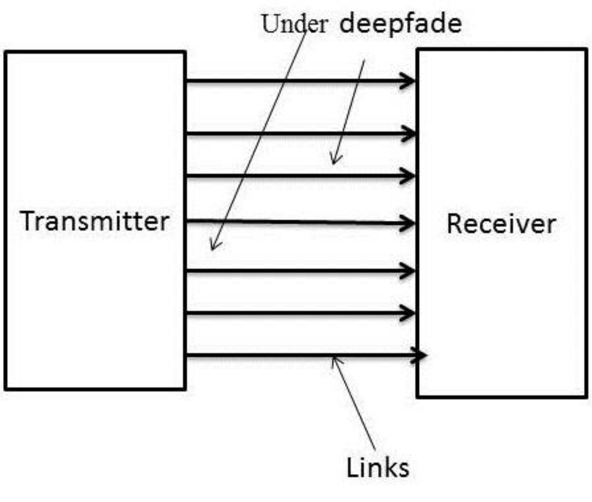

Figure 3.3: Multiple Links are using to avoid Deep fade condition.

3.3 Space Time Block Coding

Space time block code is a technique used in wireless communication to transmit multiple copies of data stream across a number of antenna and exploits the various received version of data to improve the reliability. Few data stream corrupted by the thermal noise. Corrupted by the thermal noise in the receiver means that some of copies of the data will be better then others.

Space time coding combines all the copies received signal in an optimal way to extract as much information from each of them as possible. An STBC is usually represents by a matrix each row represents a time slot and each column represents antenna's transmission over time. The code rate of an STBC measures how many symbols per time slots transmits an average over the one block. Only one standard STBC can achieve full rate (rate 1) that is the Alamouti sapce time coding [27].

3.3.1 Alamouti Code

Alamouti STBC for two transmitter antenna and two receiver antenna. At a given symbol period, two signal are simultaneously transmitted from the two antenna.the signal transmitted from antenna zero is denoted by s_0 and from antenna one by s_1. For next symbol period signal $-s_1^*$ is transmitted from zero, and signal s_0^* is transmitted from antenna one where * is the complex conjugate operation. Consider at the receiver end y(0) received signal at first time instant and y(1) received signal at the second time instant. n(0) and n(1) is additive white Gaussian noise. Received signal at first time instant.

$$y(0) = \begin{bmatrix} h_0 & h_1 \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + n(0)$$

Received signal at second time instant.

$$y(1) = \begin{bmatrix} h_0 & h_1 \end{bmatrix} \begin{bmatrix} -s_1^* \\ s_0^* \end{bmatrix} + n(1)$$

Above both the received signal we can be write in equivalent to MIMO system as

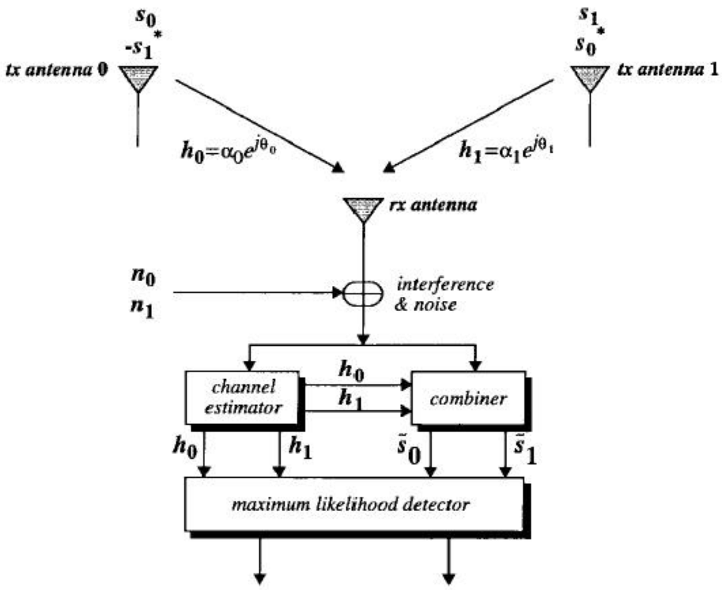

Figure 3.4: Two-branch transmit diversity scheme with one receiver and two transmitter [28].

below

$$\begin{bmatrix} y(0) \\ y(1) \end{bmatrix} = \begin{bmatrix} h_0 & h_1 \\ h_1^* & -h_0^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} n(0) \\ n(1) \end{bmatrix}$$

$$column(c_1) = \begin{bmatrix} h_0 \\ h_1^* \end{bmatrix} column(c_2) = \begin{bmatrix} h_1 \\ -h_0^* \end{bmatrix}$$

$c_1^H c_2 = h_0^* h_1 + h_1(-h_0^*) = 0$ i.e two column orthogonal to each other. Hence Alamouti belongs to a spacial class of coding termed as orthogonal space time block coding (OSTBC) and $\frac{c_1}{\|c_1\|}$ can be employed as a receive beam former to detect s_0.

Table 3.1: The encoding and transmission sequence for the two-branch transmit diversity scheme.

Time	Antenna 0	Antenna 1
Time t	s_0	s_1
Time t+T	$-s_1^*$	s_0^*

Where T is symbol duration.

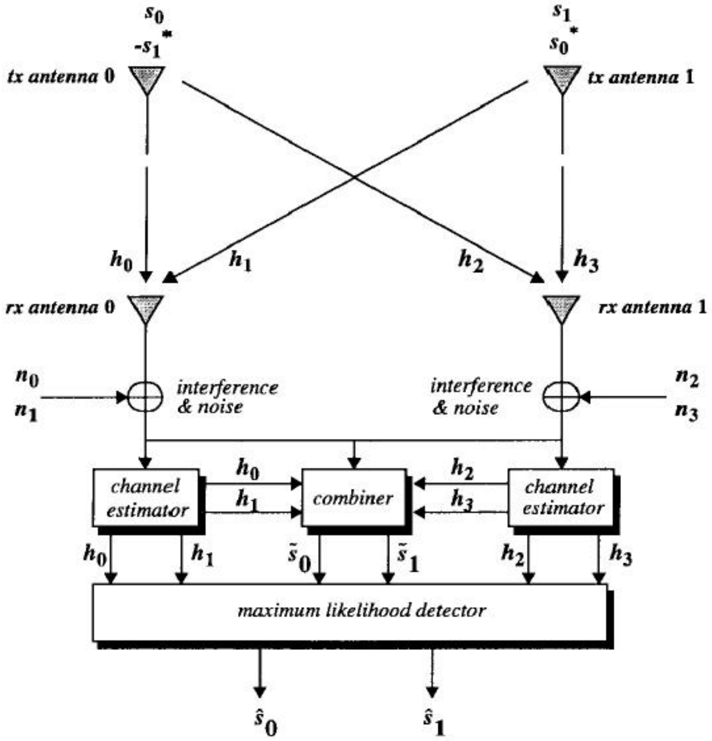

Figure 3.5: Two-branch transmit diversity scheme with two receivers and two transmitter [28].

signal to noise ratio (SNR) of alamouti is given below.

$$SNR = \frac{\|h\|^2 p_1}{\sigma_n^2} \tag{3.2}$$

p_1 is power allocated to s_0, total power transmitted is p which is fixed. If transmitted power for s_0 and s_1 is fixed which is half of the total power transmitted then SNR can write-

$$SNR = \frac{p}{2}\frac{\|h\|^2}{\sigma_n^2} \tag{3.3}$$

From Equation (3.3) Alamouti space time block coding achieve second order diversity but performance of SNR will degrade with 3 dB loss.

3.4 System Model

We consider a MIMO-OFDM system employing N_t transmit antenna and N_r receive antennas. Figure 3.6 shows schematic block diagram of Transmitter and Figure 3.7 Receiver. Data stream splits in to N-subcarrier according to number of transmitter antenna. Each subcarrier are orthogonal to each other and taking

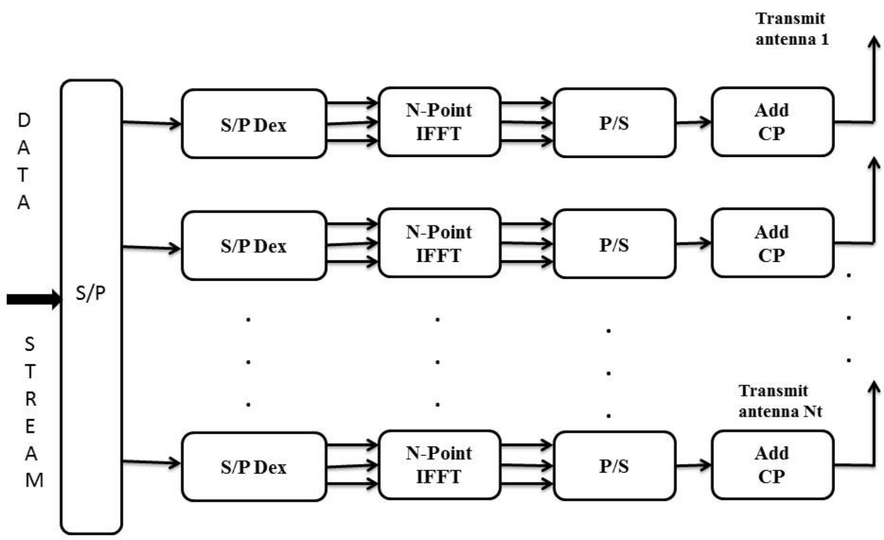

Figure 3.6: Schematic diagram of MIMO-OFDM Transmitter block.

the inverse Fourier transform (IFFT) for modulation of the data stream. We assume that m^{th} transmit antenna, $X_{l,m}(k)$ during l^{th} period of symbol. Here N_p is number of pilot symbol, so N-N_p is a data symbol which going to transmit.

$$X_{l,m}(k) = \begin{cases} D_{l,m}(k) & k \in s_d \\ P_{l,m}(k) & k \in s_p \end{cases} \tag{3.4}$$

Where s_d ands_p are indicates data stream and pilot subcarriers. Initially we assume that coarse synchronization has been successfully completed at the beginning of the data frame, only a small amount of CFO has remained for the estimation. In indoor application we assume that very strong line of side and very less amount of Doppler Effect at the receiver side. A single common CFO for the whole MIMO-OFDM system is considered. At receiver side, r^{th} receive antenna detected on the k^{th} subcarriers on the l^{th} transmitted OFDM symbol in frequency domain. Receive signal with effect of CFO is given below [29],

$$R_{l,m}(k) = \sum_{m=1}^{N_t} \hat{H}_{l,r,m}(k) X_{l,m}(k) e^{j2\pi\xi l(N+N_g)/N} + I_{l,r}(k) + W_{l,r}(k) \tag{3.5}$$

Where r = 1, 2, ... , N_t

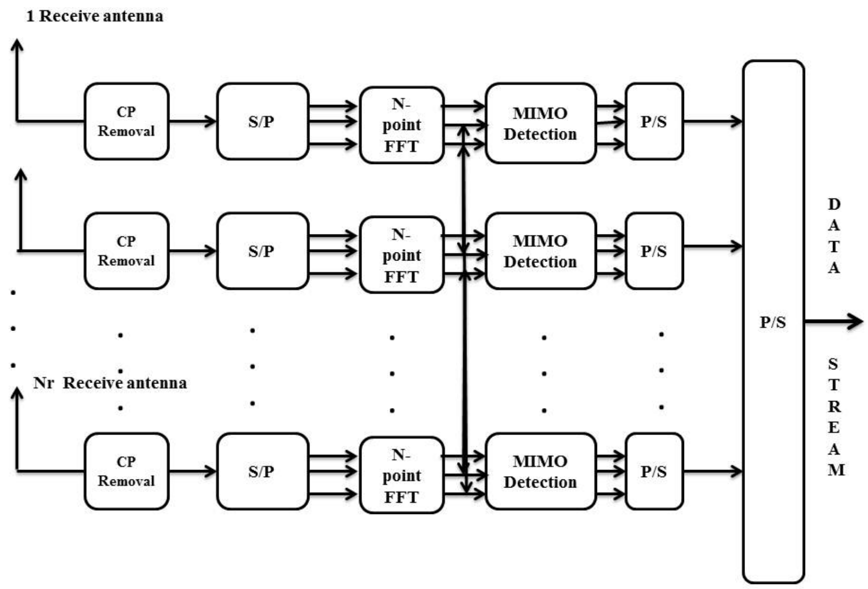

Figure 3.7: Schematic diagram of MIMO-OFDM Receiver block.

With

$$\hat{H}_{l,r,m}(k) = H_{l,r,m}(k)\frac{sin(\pi\xi)}{Nsin(\pi\xi/N)}e^{j\pi\xi(N-1)/N} \tag{3.6}$$

and

$$I_{l,r}(k) \tag{3.7}$$
$$= \sum_{m=1}^{N_t}\sum_{n\neq 1}^{N-1} H_{l,r,m}(k)X_{l,m}(k).e^{j2\pi\xi l(N+N_g)/N}\frac{sin(\pi(\xi+N-k))}{Nsin(\pi(\xi+N-k)/N)}e^{j\pi(\xi+N-k)(N-1)/N}$$

N_g is number of guard interval (GI) ξ is normalized carrier frequency offset (CFO), m is number of transmit antenna, r number of receive antenna, $H_{l,m}(k)$ is channel frequency response from transmit antenna to receive antenna, $I_{l,r}(k)$ inter-carrier interference (ICI) generated by frequency error and $W_{l,r}(k)$ is zero-mean complex Gaussian noise.

3.5 Proposed Methods

3.5.1 Conventional Estimation Scheme

The aim of frequency tracking is to estimate small CFO which remains in tracking mode for WLAN system. One simple way to increase the estimation range and estimation accuracy using two different OFDM symbols with S delay and compare these symbols. Two OFDM symbol $R_{l,r}(k)$ and $R_{l+s-1,r}(k)$ is delay with the S-1 [30]. We assume the channel is a time invariant channel for several OFDM symbol period in WLAN application. The CFO can be estimated without knowledge of the channel information by minimizing the mean square error (MSE) between the two identical transmissions [6]. This approach can be implemented in MIMO-OFDM systems [6]. Pilot symbol $P_{l,m}(k)$ is identical for N_t transmit antenna in MIMO configuration. Then a symbol by symbol correlation at the receiver is

$$\Omega_r(k) = R^*_{l,r}(k)R_{l+s-1,r}(k) \tag{3.8}$$

We assume that fading remains constant over a block of S consecutive OFDM periods. After using multiple antenna we obtain CFO estimation [29].

$$\hat{\xi} = \frac{N}{2\pi(S-1)N_u} arg\left\{\sum_{k\in s_p}\sum_{r=1}^{N_r}\Omega_r(k)\right\} \tag{3.9}$$

Where N_u = N+N_g, from above equation range of estimation is $|\xi|< N/(2(S-1)N_u)$

3.5.2 Proposed Estimation Scheme

In this section we proposed CFO tracking for MIMO-OFDM system by employing block-by-block estimation. Analysis of the optimal size of block and minimization of the MSE of frequency estimator. We use S observation symbols they are grouped into two consecutive blocks with length A and S-A. The observation symbol, in each block are added sequentially and summed results are correlated block-wise as follows.

$$\Omega_r(k) = \left\{\sum_{i=0}^{A-1} R_{i,r}(k)\right\}^* \sum_{n=A}^{S-1} R_{n,r}(k), k \in S_p \tag{3.10}$$

For averaging operation of two block can be use FIR filter. In indoor WLAN environment assuming slow-fading condition then we can write above equation as

$$\Omega_r(k) = \left|\sum_{m=1}^{N_t}\hat{H}_{l,r,m}(k)\right|^2 E_p \sum_{n=A}^{S-1}\sum_{i=0}^{A-1} e^{j\theta(n-i)} \tag{3.11}$$

E[x] is mean of x from Equation (3.8) Estimation of ξ is derived by finding the argument of summation of $\Omega_r(k)$ over all possible r's and k's in MIMO-OFDM systems i.e

$$\hat{\xi} = \frac{N}{\pi S N_u} arg \left\{ \sum_{k \in s_p} \sum_{r=1}^{N_r} \Omega_r(k) \right\} \tag{3.12}$$

3.5.3 Selection of Optimal Size Block

To choose the optimal size for block size A, we derive MSE of the proposed estimator. For the sake of simplicity we assume that the antenna are placed such that their channel transfer function can be considered as uncorrelated Re(x) and Im(x) are denote real and imaginary part of x, respectively ρ=$e^{j\theta S/2}$ and ξ is small. Then the argument term can be expressed as

$$arg \left\{ \sum_{k \in s_p} \sum_{r=1}^{N_r} \Omega_r(k)\rho \right\} = \frac{Re \left\{ \sum_{k \in s_p} \sum_{r=1}^{N_r} \Omega_r(k)\rho \right\}}{Im \left\{ \sum_{k \in s_p} \sum_{r=1}^{N_r} \Omega_r(k)\rho \right\}} \tag{3.13}$$

since $\hat{h}_{l,r,m}(k)$ are highly uncorrelated for different l's , r's and m's or $k \in S_p$. Based on the fact $E[\hat{W}_r(k)] = 0$ and some straight forward calculation the variance of the fine frequency estimator can easily derived.

$$E[|\hat{\xi} - \xi|^2] = \frac{N^2}{2\pi^2 S^2 N_u^2 N_p^2 N_t N_r (S-A)A} . \left\{ \frac{S}{SNR} + \frac{1}{N_t.SNR^2} \right\} \tag{3.14}$$

Where SNR = $\frac{\sigma_H^2}{\sigma_W^2}$. By differentiating with respect to A and solving for zero. For necessary condition equal to zero with the minimum MSE.
$(S-A)^{-2}A^{-2}(2A-S) = 0$, Since 0 <A <S, a unique solution is A = S/2. which is valid for estimation.

3.6 Simulation Results

The OFDM parameter chosen in the simulation which are based on the IEEE802.11n WLAN draft as follows: N = 64, $N_g = 16$, $N_p = 4$ and maximum Doppler frequency was assumed to 20Hz. Alamouti space time block coding is used for diversity gain.

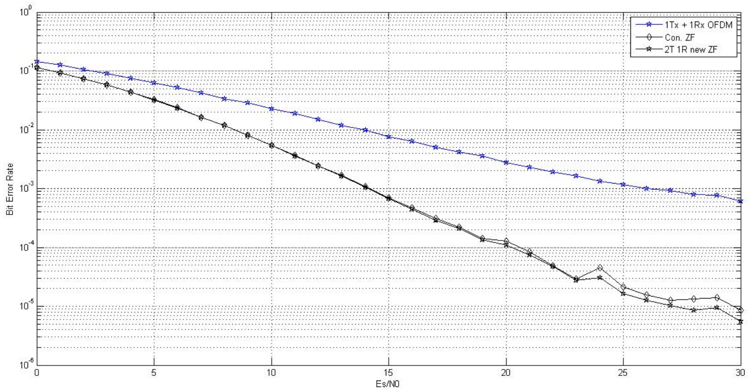

Figure 3.8: BER, after using Alamouti space time block coding for MIMO-OFDM transmission scheme and zero forcing (ZF) Receiver.

Figure 3.8 shows BER analysis of the MIMO-OFDM system with space time block coding (Alamouti coding), when $N_t = 2$, $N_r = 2$ and comparison between the conventional method of one transmitter and one receiver with zero forcing receiving methods is used.

Figure 3.9, 3.10 shows the MSE of the proposed fine frequency estimator versus the length of the first block A in sample unit, when transmitter and receiver antenna is two. Both the figure wide range of SNR taken, which is 8dB to 28dB for determining the optimal value of block A. From both figures ,there exists one specific value of A that give minimum MSE with respect to different value of SNR. i.e A = S/2 which is exactly coincides with the value derived.

Figure 3.11 compares the MSE performance of conventional method and proposed frequency estimation method with small value of the CFO. Here we have taking $N_t = 2$ and $N_r = 2$.

3.7 Conclusion

The OFDM parameters chosen the simulation is based on IEEE802.11n N = 64, N_g = 16 and $N_p = 4$. To show the independence of the optimal value of block size A to SNRs, a wide range of SNR 8 dB to 28 dB are selected. This estimation presented an improved frequency offset tracking scheme in the OFDM based MIMO-WLAN system. This can increase the estimation range of existing methods and achieves

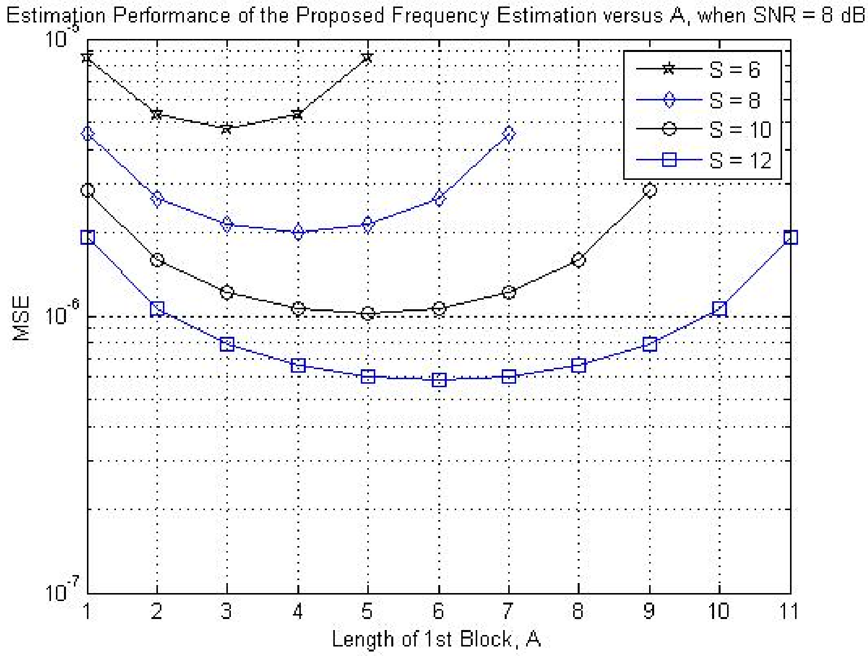

Figure 3.9: Estimation performance of the proposed frequency estimator versus A in SNR = 8dB.

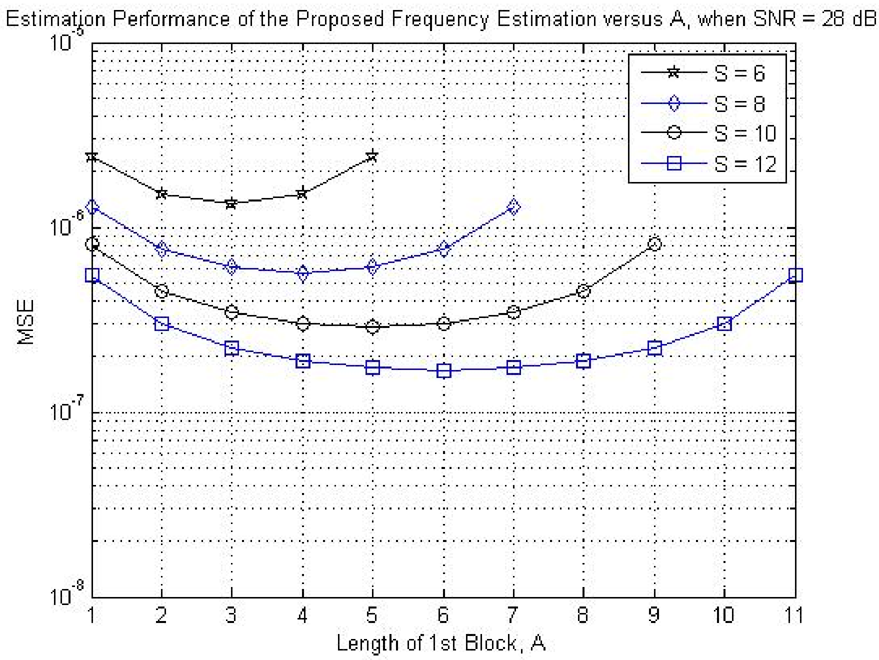

Figure 3.10: Estimation performance of the proposed frequency estimator versus A in SNR = 28dB.

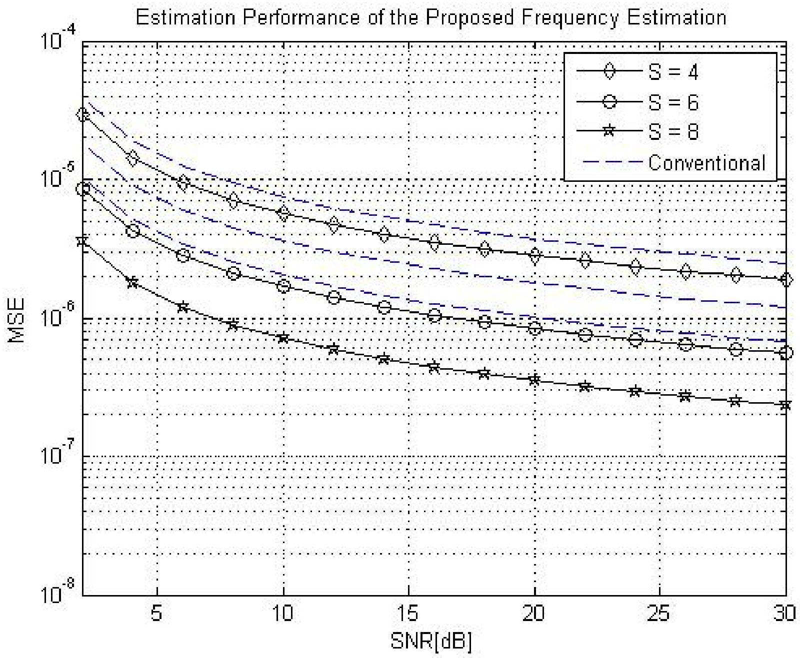

Figure 3.11: Estimation performance of the proposed frequency estimator when $N_t = 2$, $N_r = 2$.

better estimation performance. The design of our algorithm is such that it can be very easily applied to any pilot based OFDM system in the indoor wireless system.

4
Concluding remarks

4.1 Conclusion

These estimates presented an improved frequency offset tracking in OFDM and MIMO-OFDM system. Space time block coding is used for increasing the diversity gain in the MIMO system. Where Alamouti space time block coding is used which code rate and accuracy is high.

- Chapter 2 explains the carrier frequency offset estimation in OFDM systems. CFO estimation has been performed by using four basic estimation method and compression between them. CP based estimation, symbol-by symbol estimation, a pilot based estimation and training sequence based estimation are used for OFDM estimation. The simulation results show the superior performance of our proposed scheme in AWGN channel. A pilot based mean square estimation (MSE) performance is superior then compare to CP based and symbol based. By using repeated sequences with different value of D, the CFO has been estimated.

- MIMO-OFDM system design and carrier frequency offset estimation is explained in chapter 3. These estimates presented an improved frequency offset tracking scheme in the OFDM based MIMO-WLAN system. This can increase the estimation range of existing methods and achieves better estimation performance. Here block by block estimation method is used. In this method comparisons between two blocks with some specific delay and minimize the mean square error (MSE). For this minimum MSE, we optimize the optimal block size. Space time block coding is used for the diversity gain in MIMO transmission. For STBC, Alamouti coding is used. Design method is easily applied for any pilot based OFDM systems.

4.2 Future work

- Further intensive research is needed in MIMO-OFDM system considering the generalized system model. Where the CFO and propagation delay between each transmit antenna and receive antenna are possibly different.

- For high Doppler shift in an indoor and outdoor application for coarse and fine CFO estimation in MIMO-OFDM systems.

- Time offset (STO) and frequency offset estimation combinable in OFDM and MIMO-OFDM systems.

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